# Functionalization of silicon surfaces with Si–C linked β-cyclodextrin monolayers†

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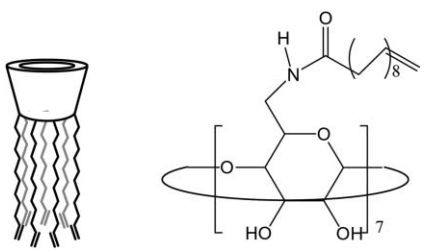
**Vinyl-terminated heptapodyl β-cyclodextrins react with hydrogenated silicon surfaces to generate covalently-bound molecular recognition devices.**

Molecular host–guest recognition systems have attracted considerable attention in the last two decades. Supramolecular inclusion of a guest into the host materials can serve many purposes including: protection against photochemical degradation, soft surface-patterning method for nanotechnology, chemical sensors, and molecular electronics. A widely studied class of natural host molecules are cyclodextrins, cyclic oligosaccharides consisting of six (α), seven (β) or eight (γ) glucopyranose units. These water-soluble compounds are toroidally shaped with a hydrophobic internal cavity and a hydrophilic external surface, which enable complexation of organic molecules in water *via* hydrophobic interactions.[1] The 2D confinement of cyclodextrins onto surfaces is however a prerequisite for processing valuable molecular devices. Attachment of cyclodextrin monolayers onto surfaces presents a challenging topic for many research groups.[2] Particularly worth outlining is the very elegant work of Reinhoudt and co-workers who developed the concept of molecular printboard and micro-contact printing.[3] Most of the reported research devoted to immobilization of cyclodextrins used gold surfaces as substrates. Nevertheless, at the molecular device level, with the perspective of a "bottom-up" nanofabrication strategy, silicon technology is highly desirable. Only a few studies, utilizing silicon oxide surfaces, report on the formation of cyclodextrin assemblies on silicon substrates.[4]

In this communication, we report the covalent attachment of cyclodextrin macromolecules to a silicon surface by the photochemical reaction between a hydrogen-terminated monocrystalline silicon surface (Si–H) and 1-alkene chains ω-substituted by β-cyclodextrin. This mild procedure affords the formation of organic monolayers through Si–C interfacial bonds and is not too harsh towards fragile molecules such as cyclodextrins or bioactive materials.[5] A major advantage of this approach is that it does not require or produce a silicon oxide layer which would serve as an additional insulating (often electronically defective) barrier. Moreover, the molecular films produced from the reaction of Si–H with ω-substituted 1-alkenes have been demonstrated to be well-ordered, densely packed and robust monolayers.[6] Crystalline silicon is a very attractive alternative substrate for immobilizing macromolecules because of its well-defined structure and the ease and reproducibility of the preparation of the hydrogen-terminated surfaces. In addition to these important technological features, modification of the hydrogenated crystalline silicon offers the possibility of monitoring the host–guest interaction (between cyclodextrin and a guest) using both fluorescence and electrochemical measurements. Indeed, sequential reactions of patterned DNA onto hydrogenated crystalline silicon have been studied by fluorescence spectroscopy.[7,8] The use of fluorescence techniques with gold substrates is limited because the gold surface plasmons resonance hampers the signal of many fluorescent probes while electrochemical detection cannot be achieved with electrically insulating silicon oxide substrates.

Cyclodextrin-modified silicon surfaces were prepared by irradiating for 5 h at 300 nm a Si(111)–H (boron-doped, *p*-type, 1–5 Ω cm) surface in a toluene solution containing *ca.* $10^{-2}$ mol $dm^{-3}$ β-cyclodextrin heptasubstituted by 1-alkene chains (heptakis{6-deoxy-6-[undec-10-enamido]}-β-cyclodextrin, see ESI). The long vinyl-terminated chains were introduced on the primary hydroxyl rim of β-cyclodextrins (Scheme 1). Since the primary hydroxyl groups are directed to the narrow side of the cyclodextrins, the secondary hydroxyl rim is left free, allowing the wider side to be fully accessible after subsequent grafting. Heptapodyl β-cyclodextrin containing seven anchoring sites per molecule is preferred over monofunctionalized compounds to ensure a more efficient packing of the cyclodextrins onto the surface and a more robust architecture.[9]

The first difficulty to address is the possible reaction of the hydroxyl groups of the β-cyclodextrin secondary side with Si–H. Indeed, amines, carboxylic acids, aldehydes and alcohols have been reported to react with hydrogen-terminated silicon.[10] Numerous studies have shown that the reaction of OH-bearing




**Scheme 1** Structure of the heptapodant β-cyclodextrin used in the preparation of functionalized monolayers on silicon surfaces.

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bifunctional molecules (*e.g.* undecylenic acid) with hydrogen-terminated silicon can occur selectively at the alkene units.[8,11] We thus reasoned that the modified cyclodextrins may be immobilized on silicon *via* the alkene functions (*vide infra*). Transmission FTIR spectroscopy performed with modified *porous* Si(100) surfaces was used to probe the attachment of the cyclodextrin derivatives on silicon.[12] Because the chemistry of *porous* silicon is similar to that of *flat* silicon crystals, this technique is a very powerful tool for the identification of surface species.[13] FTIR spectra of hydrogen-terminated *porous* Si(100), bulk heptapodant β-cyclodextrin derivatives (as KBr pellets) and cyclodextrin-modified Si(100) were recorded and compared. In the 4000–2000 $cm^{-1}$ region, the characteristic vibration bands of cyclodextrin can be identified in both the bulk and the grafted sample spectra ($\sim$3300 $cm^{-1}$, broad stretching ν(O–H); 2930 and 2850 $cm^{-1}$, antisymmetric and symmetric stretching $\nu_a$(C–H) and $\nu_s$(C–H) of the $CH_2$ groups, respectively). These features are absent from the bare Si spectrum. Fig. 1 displays the spectra recorded in the 2200–400 $cm^{-1}$ region. Vibration bands of cyclodextrin can also be seen in both the bulk and the grafted sample spectra, but many bands in the latter are overlapped by those of the underlying Si substrate. These observations provide strong evidence for the presence of cyclodextrin derivatives at the Si surface but also indicate, as expected, that the Si surface is not fully covered by the β-cyclodextrins. In particular, considering the ν(Si–$H_x$) stretching modes at *ca.* 2100 $cm^{-1}$ in the bare Si and the grafted sample spectra, respectively, a clear decrease of the intensity of these bands is observed after the grafting reaction (Fig. 1a, 1b).

The bulk spectrum displays a broad band centered at 1660–1647 $cm^{-1}$ that can be reasonably ascribed to the overlapping of two stretching mode vibrations ν(C=C) (in R-CH=$CH_2$ type molecules, 1650–1640 $cm^{-1}$) and ν(C=O) (in amide type molecules, 1660–1710 $cm^{-1}$).[14] Interestingly, a corresponding slimmer band shifted to 1670 $cm^{-1}$ can be seen in the grafted sample spectra, indicating that only the ν(C=O) contribution is still visible. This result suggests that the β-cyclodextrin derivatives mainly react with the hydrogenated silicon surface through the alkene moieties.

Fig. 2 shows the voltammetric responses of the redox probe $Fe(CN)_6^{3-/4-}$ in an aqueous electrolyte at β-cyclodextrin- and ethyl undecanoate-modified *flat* Si(111) electrodes.[15] Since ethyl undecylenate has been shown to yield highly ordered compact monolayers by reacting with hydrogenated silicon crystals, the ester-modified surface is used as a qualitative standard for the

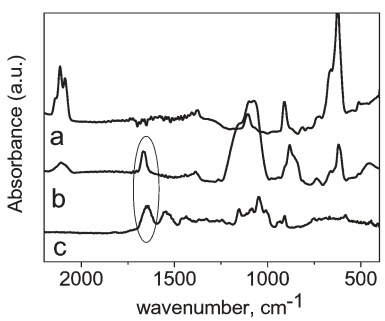


**Fig. 1** FTIR spectra of porous Si(100) crystals: (a) hydrogen-terminated sample and (b) after the photochemical reaction with the heptapodyl β-cyclodextrin. (c) Bulk spectrum of the modified cyclodextrin in KBr.

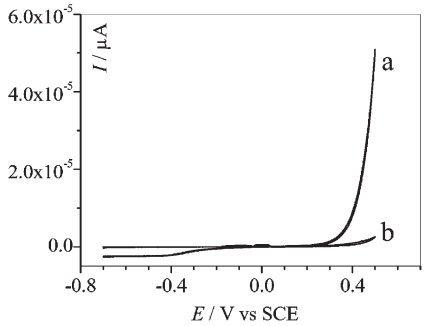


**Fig. 2** Cyclic voltammograms of 2 mM $K_3[Fe(CN)_6]/K_4[Fe(CN)_6]$ in 1 M KCl at (a) heptapodyl β-cyclodextrin- and (b) ethyl undecanoate-modified *p*-type Si(111) surfaces. Scan rate: 200 mV $s^{-1}$.

characterization of the β-cyclodextrin monolayers.[16] The blocking effect toward the $Fe(CN)_6^{3-/4-}$ redox couple is clearly observed at the ester monolayer. The absence of a significant current response reveals that the ester monolayer is densely packed and blocks the redox processes quite well. However, larger currents are measured with the β-cyclodextrin monolayer, suggesting the presence of many more defects in the film structure as compared with the ester monolayer. Tafel treatment of the voltammetric data allows for the calculation of the charge-transfer resistance $R_{ct}$ for the two different modified electrodes.[17] The obtained values are in fairly good agreement with those determined from electrochemical impedance spectroscopy measurements. Average $R_{ct}$ values of 1.4 $\pm$ 0.2 MΩ were found for the β-cyclodextrin monolayer while a higher resistance, 5.8 $\pm$ 0.2 MΩ, was obtained with the ester monolayer. Furthermore, the total capacitance values $C_{tot}$ which were fitted using a classical Randles electrical circuit (see ESI) were found to be somewhat similar for the two monolayers, namely 2.3 $\pm$ 0.5 and 2.4 $\pm$ 0.2 μF $cm^{-2}$ for the β-cyclodextrin- and ester-modified surfaces, respectively. If one considers that the β-cyclodextrin monolayer is thicker than the ester monolayer, such a result would indicate a larger dielectric constant $\varepsilon_m$ for the β-cyclodextrin monolayer which is consistent with a more defective and less densely packed monolayer.[18] This outcome reflects the large cross-section area of the heptapodyl cyclodextrins and probably their poor lateral interaction when immobilized.

Impedance spectroscopy was also used to quantitatively monitor the complexation of the guest 1-anilinonaphthalene-8-sulfonate (1,8-ANS) at the β-cyclodextrin monolayer with the negatively charged $Fe(CN)_6^{3-}/Fe(CN)_6^{4-}$ as the reporter couple.[2] 1,8-ANS is well-known for forming inclusion complexes with β-cyclodextrin in aqueous solutions.[19] Binding of this anionic guest to the β-cyclodextrin monolayer is expected to result in an increase of the charge-transfer resistance by electrostatic repulsion between the 1,8-ANS anion and the $Fe(CN)_6^{3-}/Fe(CN)_6^{4-}$ redox couple. Addition of an increasing amount of guest induced a regular increase of the $R_{ct}$ values as shown in Fig. 3. For low guest concentrations (5 μM), $R_{ct}$ values drastically increased to finally reach a constant value for concentrations higher than 70 μM, indicating the saturation of monolayer cavities. In contrast, the addition of 1,8-ANS to the ester monolayer did not lead to significant changes in the $R_{ct}$ values (see ESI). This result offers strong evidence that the guests complex in the β-cyclodextrin cavities. Also this strengthens the idea that heptapodyl cyclodextrins are bound to

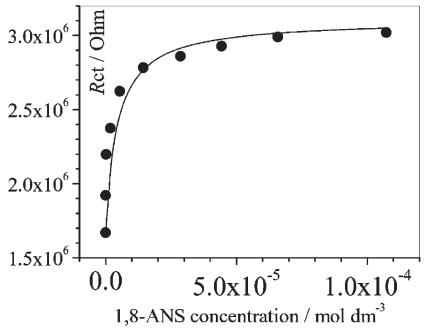


**Fig. 3** Variation of $R_{ct}$ of the β-cyclodextrin-modified monolayer with the concentration of the anionic 1,8-ANS guest. $R_{ct}$ values were determined from impedance spectroscopy measurements. The solid line is a fitted Langmuir isotherm.

silicon surfaces through the alkene moieties. The experimental $R_{ct}$ data were fitted to a Langmuir isotherm considering that filled and empty β-cyclodextrin cavities are a set of parallel resistances (equation 1).[2]

$$\frac{1}{R_{ct}} = \frac{1}{(1+Kc)R_0} + \frac{Kc}{(1+Kc)R_\infty} \quad (1)$$

where $R_0$ is the experimental value of $R_{ct}$ in the absence of 1,8-ANS, $R_\infty$ is the calculated $R_{ct}$ value for the total saturation of the cyclodextrin cavities, $c$ is the concentration of 1,8-ANS and $K$ is the binding constant. The fitting procedure gave a binding constant of $3.9 \pm 0.3 \times 10^5$ $M^{-1}$ for 1,8-ANS at the β-cyclodextrin monolayer. This value is considerably larger than that obtained from fluorescence measurements in aqueous 1 M KCl solution for 1,8-ANS interacting with hydroxypropyl-β-cyclodextrin (300 $M^{-1}$). Similar results have been reported by Reinhoudt and co-workers for self-assembled monolayers of β-cyclodextrin thiolated adsorbates on gold and were attributed to a confinement effect.[2] However, it is believed that the imperfect structure of our cyclodextrin monolayers should be considered for modelling the $R_{ct}$ variations. Further work is currently being performed to fully understand the molecular recognition phenomena at our silicon/β-cyclodextrin hybrid junctions.

In conclusion, this preliminary work demonstrates the covalent attachment of heptakis{6-deoxy-6-[undec-10-enamido]}-β-cyclodextrin onto silicon surfaces. The grafting was achieved using a mild photochemical reaction between hydrogen terminated silicon and cyclodextrins substituted by 1-alkene chains. Both IR and electrochemical characterizations strongly suggest that the β-cyclodextrins are anchored to the surface *via* the alkene moieties. As a result, the cyclodextrin cavities are fully accessible and the immobilized compounds retain their binding ability.

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